on the origin of sunspots

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Received ___ ..- _..- . . ---- ; accepted .

ABSTRACT

It is proposed that sunspots (and other flux emergence phenomena) originate due to the presence of fluctuating magnetic fields complementing the regular, mean field in the convection zone. The mean field predicted by dynamo theories is too weak itself to emerge at the surface of the Sun. However the total magnetic field (mean plus fluctuations) at random times becomes sufficiently strong to emerge at the solar surface. In this way the mean field is responsible for observed regularities of the sunspot magnetic fields, such as the Hale's law and the 11-year periodicity, and the fluctuations are responsible for emergence of the magnetic field of individual sunspots.

1. introduction

The early concept of the origin of sunspots (Babcock 1961, Parker 1979) was based on the idea of a magnetic loop emerging from the convective zone to the solar surface due to buoyancy. The magnetic loops were assumed to be caused by instabilities of the largescale, mean magnetic field generated by the joint action of the differential rotation and mean helicity of the convect ion (dynai no). The mean field had the form of waves propagating from the poles to the equator in 11 -years. This concept explained the solar sun ispot cycle in its basic manifestations: the M aun ider butterfly diagram and H ale's law of the field polarities. The idea of the mean field generation and its evolution was justified and developed in numerous st udies (c. f. Moffatt 1978, Parker 1979, Krause &R 'adler 1981, Zeldovich, Ruzmaikin & Sokoloff 1983). Theories of instabilit ies leading t o the formation of emerging magnetic loops were less advanced however.

Recently a mo del of storage, instability and dynamical eruption of magnetic flus tubes in the convection zone has been developed (Schüssler et al. 1994. Caligari 1 995). According to this model, a toroidal flux tube stored at the overshoot layer becomes unstable and erupts to the surface of the Sun when its field strength exceeds 1():' G. Weaker fields arc either stal)] c Or grow to(-) slowly. The model is in a good agreement with the basic observational facts related to sunspot magnetic fields in that the flux tubes emerge at low heliolatitudes and have the correct inclination and asymmetry with respect to the east-west direction. llov'ever, there is still a problem to resolve. Conventional dynamo theories do not predict such a strong magnetic field. The predicted field dots not exceed the equipartition field which is only about 104 G (Schüssler et, al. 1 994).

This paper suggests solving this problem by taking into account the random, fluctuating magnetic fields in the solar convection zone. Although there are regularities in sunspots behavior, within these regularities each sunspot appears at a random time and at a random site. The number of sunspots observed in a given cycle fluctuates. In addition, the simple question of why sunspots occupy so small an area on the solar surface (less than or about 1%) becomes a problem if we relate the sunspot origin to only the mean magnetic field.

The importance of fluctuating fields is indicated by observations. It has been noted that there is no single large flux tube in the sunspot formation. Instead, the sunspot magnetic field is assembled over a period of hours and days through the progressive gathering of many flux tubes (Zwaan 1978). In accord with these observations the original concept has been developed in such a way that "the sunspot appears as a dynamical clustering of many separate flux tubes, pressed together to form a single flux tube at the surface, but otherwise distinct and separate within the interior of the Sun" (Parker 1979). However, in this development the flux tubes were treated as regular and non-random.

Here the randomness of sunspot field is considered as a very important factor. We use the idea, discovered in the study of dynamical systems (see for example Wiesenfeld & Moss 1995), that noise plays a constructive role in detection of weak periodic signals. This phenomenon is called "stochastic resonance". Although it has been recognized that it is not a true resonance effect, the term is still in use. The present paper will not use this term and is restricted to the simplest model of the noise-periodic signal interaction.

2. The formation of sunspots as a threshold-crossing phenomenon

Assume that sunspots originate according to the scenario described in the model (Schüssler et al. 1994, Caligari 1995) but with the relatively weak (subthreshold) mean field generated by dynamo. The crossings of the 10^5 G threshold, required for the fields to emerge to the solar surface, will be provided with the help of fluctuating magnetic fields (noise) superimposed on the mean field. The presence of the mean field explains the basic observational regularities and relates sunspots to the solar cycle. Thus, the basics of the original concept are preserved. However, an important new element appears: the noise (turbulence) is strong enough to permit the magnetic flux emergence.

To produce the mean field, regular motions such as differential rotation, and correlations such as kinetic helicity, are needed (Moffatt 1978, Parker 1979, Krause & R'adler 1981). The fluctuating magnetic fields are produced by the same convection which drives the dynamo. The generation of the fluctuating, magnetic field is less demanding: any three-dimensional random motions are sufficient (Zeldovich, Ruzmaikin & Sokoloff 1983, Molchanov, Ruzmaikin & Sokoloff 1983). An important feature of fluctuations is the absence of an upper limit on their magnitude. Although the variance of fluctuations is limited, say by the equipartion between the kinetic and magnetic energies, the occurrence of large random deviations is restricted only by the form of the distribution function of the fluctuating field. General considerations snow that this distribution function is not Gaussian, it has a larger probability for the occurrence of strong *fields* (Molchanov, Ruzmaikin & Sokoloff 1983). As an example the threshold crossing model with an exponentially distributed noise is used below. (The mean value, calculated with the help of the distribution function, is subtracted to provide zero-mean fluctuations.) The exponential is used as an approximation of the distribution function for strong fields. In principle Gaussian noise could be used but it is less effective, i.e. gives fewer crossings.

Consider a simple system which consists of a threshold, a subthreshold periodic signal and noise (see the upper panel of Fig. 1). The threshold is identified with $H_{th} = 10^5$ G. The periodic signal represents the mean magnetic field B generated by the dynamo. The noise is a random, fluctuating magnetic field b. Both the amplitude of the periodic field and the variance of fluctuating fields are assumed to be subthreshold. The threshold is crossed at the times when the total field $H = B + b$ is large enough, i.e. $H > H_{th}$. The threshold crossings is a random signal modulated by the periodic mean field. Each crossing can be interpreted as a flux tube emergence. The number of crossings per a certain time interval simulates the sunspot number. The simulation was carried out for 1 1(1 "year" sample with the 1 day time unit. A particular realization is shown in Fig. 1. (For the sake of clarity only a half of the interval and only every 30-th point of the random curve are shown in the upper panel of Fig. 1.) The 1(W panel Snows the "annual" number of cross ings.

The spectrum of the number of crossings per year is shown in Figure 2 compared with the spectrum of the real sunspot number (Fig. 3). One can see a qualitative similarity between the two. Note that in both the model and observed spectra the 11-year periodicity arises on top of a noise spectrum. This type of spectrum is typical of "stochastic resonance" phenomena observed in different physical and biological experiments (Wiesenfeld & Moss 1995). In that sense the basic approach adopted in this paper is supported by observations.

3. Discussion

Thus the dynamo can produce a relatively weak magnetic field so that this field is not able to emerge at the surface of the Sun. However in the presence of magnetic fluctuations, which also can have a subthreshold variance, the flux can emerge. The mean field however plays an important role in producing the observed features of the sunspots magnetic field and the solar cycle. The simple model presented in this paper serves only as a qualitative! demonstration of this effect. More sophisticated models which will include the spatial distribution of the magnetic field (dynamo waves for the mean field) and a more realistic distribution function for the fluctuating fields are under development.

I thank J. Feynman for helpful comments. This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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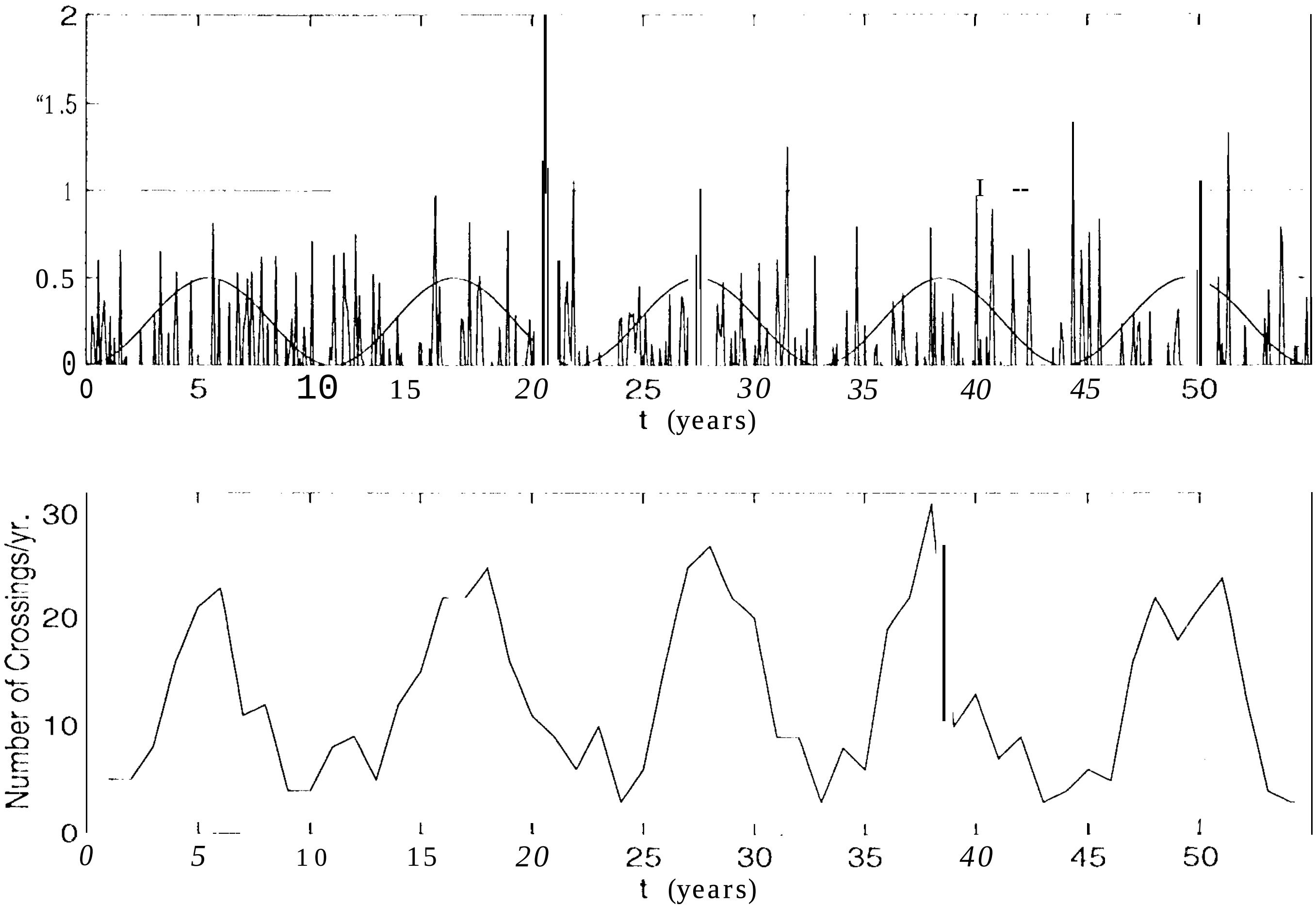

Fig. 1.- A threshold (the straight line of the unit height), a subthreshold 11-year periodic signal of 0.5 amplitude and the exponentially distributed noise of a variance 0.3. When the sum of the fluctuating and mean fields exceed the threshold a crossing occurs, simulating a magnetic loop emerging at the surface of the Sun. The number of crossings per year is shown on the low panel.

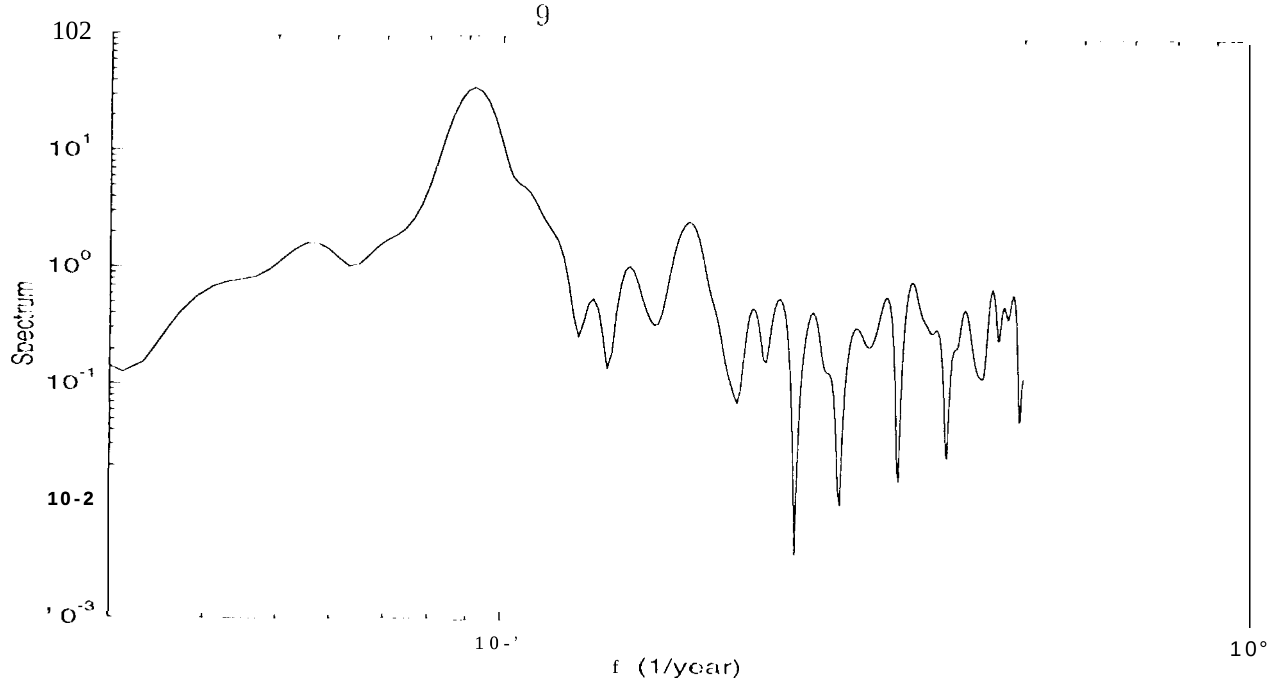

Fig. 2.- The spectrum of the number of crossings per year, i.e. of the signal shown on the second panel of Figure 1.

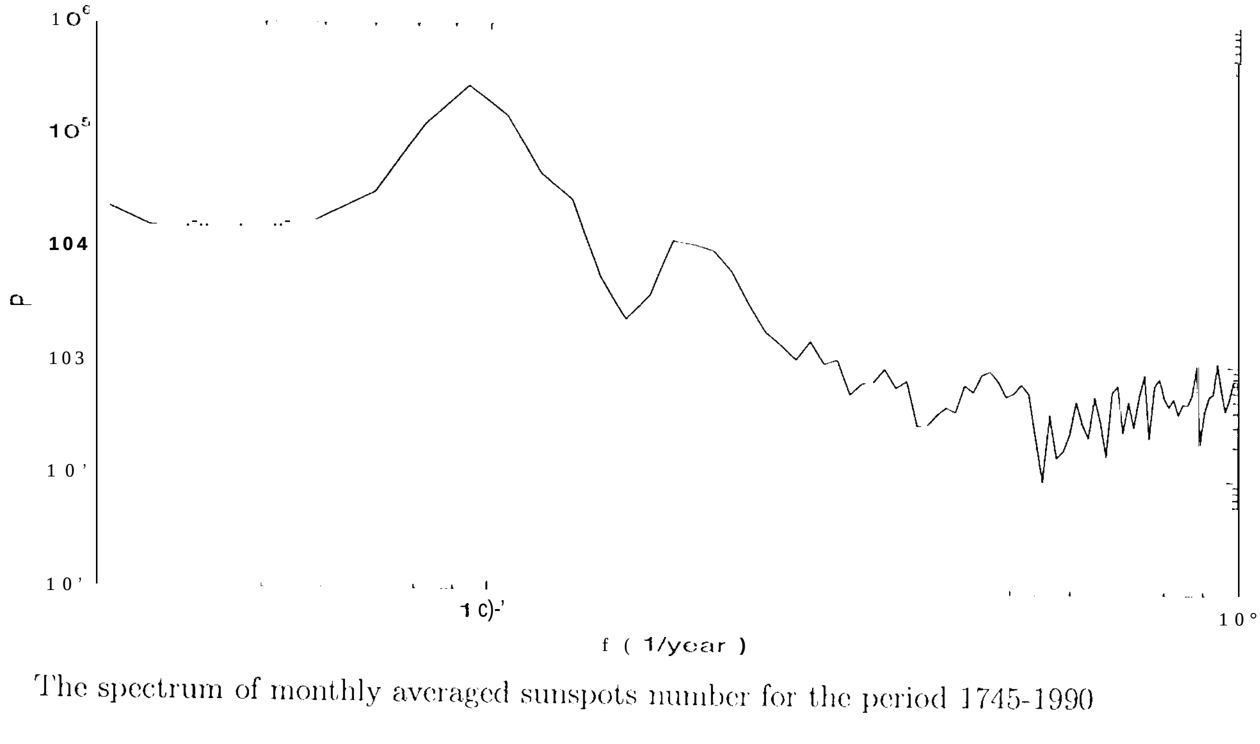

Fig. 3.- The spectrum of monthly averaged sunspots number for the period 1745-1990